

EVALUATION OF Ti-48Al-2Cr-2Nb UNDER FRETTING CONDITIONS

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SUMMARY

An investigation was conducted to examine the fretting behavior of γ -TiAl (Ti-48Al-2Cr-2Nb) in contact with a nickel-base superalloy (Inconel 718) in air at temperatures from 23 to 550 °C. Fretting wear experiments were conducted with 9.4-mm-diameter hemispherical Inconel (IN) 718 pins in contact with Ti-48Al-2Cr-2Nb flats (and the reverse) at loads from 1 to 40 N and fretting frequencies from 50 to 160 Hz with slip amplitudes from 50 to 200 μ m for 1 to 20 million fretting cycles. The results were similar for both combinations of pin and flat. Reference fretting wear experiments were also conducted with 9.4-mm-diameter hemispherical Ti-6Al-4V pins in contact with IN718 flats.

The interfacial adhesive bonds between Ti-48Al-2Cr-2Nb and IN718 in contact were generally stronger than the cohesive bonds in the cohesively weaker Ti-48Al-2Cr-2Nb. The failed Ti-48Al-2Cr-2Nb subsequently transferred to the IN718 surface at any fretting condition. The wear scars produced on Ti-48Al-2Cr-2Nb contained metallic and oxide wear debris, scratches, plastically deformed asperities, cracks, and fracture pits. Oxide layers readily formed on the Ti-48Al-2Cr-2Nb surface at 550 °C, but cracks easily occurred in the oxide layers. Factors including fretting frequency, temperature, slip amplitude, and load influenced the fretting behavior of Ti-48Al-2Cr-2Nb in contact with IN718. The wear volume loss of Ti-48Al-2Cr-2Nb generally decreased with increasing fretting frequency. The increasing rate of oxidation at elevated temperatures up to 200 °C led to a drop in wear volume loss at 200 °C. However, the fretting wear increased as the temperature was increased from 200 to 550 °C. The highest temperatures of 450 and 550 °C resulted in oxide film disruption with generation of cracks, loose wear debris, and pits on the Ti-48Al-2Cr-2Nb wear surface. The wear volume loss generally increased as the slip amplitude increased. The wear volume loss also generally increased as the load increased. Increasing slip amplitude and increasing load both tended to produce more metallic wear debris, causing severe abrasive wear in the contacting metals.

1.0 INTRODUCTION

Adhesion, a manifestation of mechanical strength over an appreciable area, has many causes, including chemical bonding, deformation, and the fracture processes involved in interface failure. A clean metal in contact with a clean metal will fail either in tension or in shear because some of the interfacial bonds are generally stronger than the cohesive bonds in the cohesively weaker metal (ref. 1). The failed metal subsequently transfers to the other contacting metal. Adhesion undoubtedly depends on the surface cleanliness, the area of real contact, the chemical, physical, and mechanical properties of the interface, and the modes of junction rupture. The environment influences the adhesion, deformation, and fracture behaviors of contacting materials in relative motion.

Clean surfaces can be created by repeated sliding, making direct contact of the fresh, clean surfaces unavoidable in practical cases (ref. 2). This situation applies in some degree to contact sliding in air, where fresh surfaces are continuously produced on interacting surfaces in relative motion. Microscopically small surface-parallel relative motion, which can be vibratory (in common fretting or false brinnelling) or creeping (in common fretting), produces fresh, clean interacting surfaces and causes junction (contact area) growth in the contact zone (refs. 3 to 5).

Fretting wear produced between contacting elements is adhesive wear taking place in a nominally static contact under normal load and repeated microscopic vibratory motion (refs. 6 to 10). The most damaging effect of fretting is the possibly significant reduction in fatigue capability of the fretted component even though the wear produced by fretting appears to be quite mild (ref. 10). It was reported that the reduction in fatigue strength by fretting of Ti-47Al-2Nb-2Mn with 0.8 vol.% TiB₂ was approximately 20 percent.

Fretting fatigue is a complex problem of significant interest to aircraft engine manufacturers (refs. 11 to 14). Fretting failure can occur to a variety of engine components. Numerous approaches, depending on the component and the operating conditions, have been taken to address the fretting problem. The components of interest in this investigation were the fan and compressor blades. Many existing fan and compressor components have titanium

alloy disks and airfoils. A concern for these airfoils is the fretting in fitted interfaces at the dovetail. Careful design can reduce fretting in most cases but not completely eliminate it, because the airfoils frequently have a skewed (angled) blade-disk dovetail attachment, which leads to a complex stress state. Further, the local stress state becomes more complex when the influence of metal-metal contact and the edge of contact is evaluated.

Titanium and titanium-base alloys in the clean state will exhibit strong adhesive bonds (refs. 2 and 15) when in contact with themselves and other materials. This adhesion causes heavy surface damage and high friction in practical cases.

The objective of this investigation was to evaluate the extent of fretting damage on γ -TiAl (Ti-48Al-2Cr-2Nb) in contact with a nickel-base superalloy (Inconel 718) at temperatures from 23 to 550 °C. Reference experiments were also conducted with Ti-6Al-4V. Because the controlling operating parameters in common fretting, which are the specifics of the microscopic surface-parallel motion, such as fretting frequency, slip amplitude, and load, have not been completely identified, these parameters were examined in this study. Vertically scanning interference microscopy (noncontact optical profilometry) was used to evaluate surface characteristics, such as surface topography, surface roughness, material transfer, and wear volume loss. Scanning electron microscopy with energy-dispersive spectroscopy was used to determine the morphology and elemental composition of fretted surfaces, transferred material, and wear debris.

2.0 MATERIALS

The Ti-48Al-2Nb-2Cr specimens were of the following composition (in atomic percent): titanium, 47.9; aluminum, 48.0; niobium, 1.96; chromium, 1.94; carbon, 0.013; nitrogen, 0.014; and oxygen, 0.167. The Vickers hardness was 3.8 GPa. The tensile properties were as follows:

Temperature, °C	Modulus, GPa	Ultimate tensile strength, MPa
23	170	410
650	140	460

The nickel-base superalloy, Inconel (IN) 718, specimens were of the following nominal composition (in weight percent): nickel, 50–55; chromium, 17–21; iron, 12–23; niobium plus tantalum, 4.75–5.5; molybdenum, 2.8–3.3; cobalt, 1; titanium, 0.65–1.15; aluminum, 0.2–0.8; silicon, 0.35; manganese, 0.35; copper, 0.3; carbon, 0.08; sulfur, 0.015; phosphorus, 0.015; and boron, 0.006. The Vickers hardness was 4.8 GPa. The reference specimens examined were of the nominal composition (in weight percent) Ti-6Al-4V. The Vickers hardness was 3.9 GPa.

3.0 EXPERIMENTS

Figure 1 presents the fretting wear apparatus used in the investigation. Fretting wear experiments were conducted with 9.4-mm-diameter hemispherical IN718 pins in contact with Ti-48Al-2Cr-2Nb flats (and 6-mm-diameter hemispherical Ti-48Al-2Cr-2Nb pins in contact with IN718 flats) in air at temperatures from 23 to 550 °C. All fretting wear experiments were conducted at loads from 1 to 40 N and frequencies of 50, 80, 120, and 160 Hz with slip amplitudes from 50 to 200 μ m for 1 to 20 million cycles. Two or three fretting experiments were conducted with each material couple at each fretting condition in each environment. The data were averaged to obtain the wear volume losses of Ti-48Al-2Cr-2Nb or Ti-6Al-4V. Reference fretting wear experiments were conducted with 9.4-mm-diameter hemispherical Ti-6Al-4V pins in contact with IN718 flats.

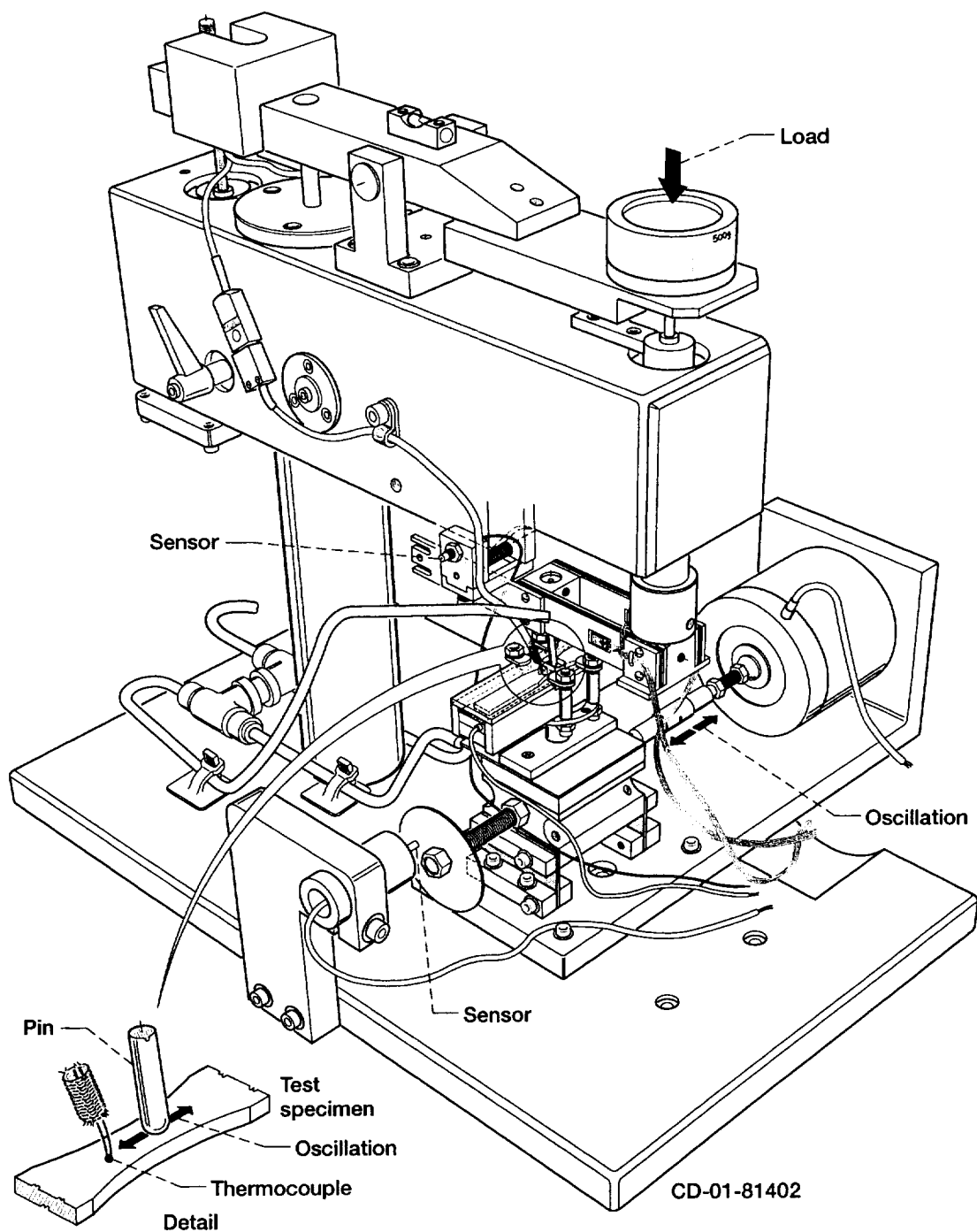


Figure 1.—Fretting apparatus.

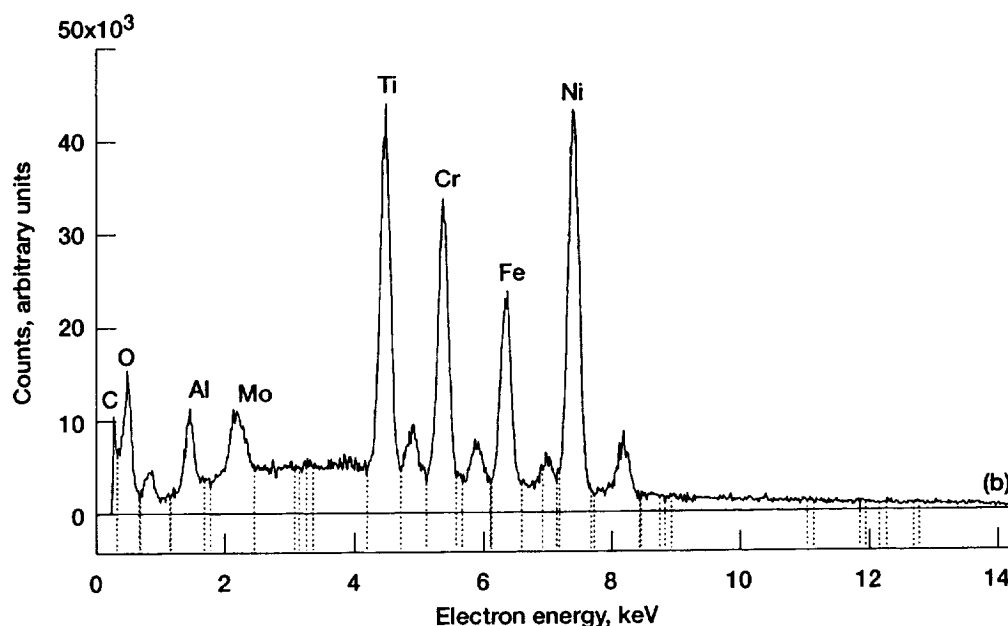
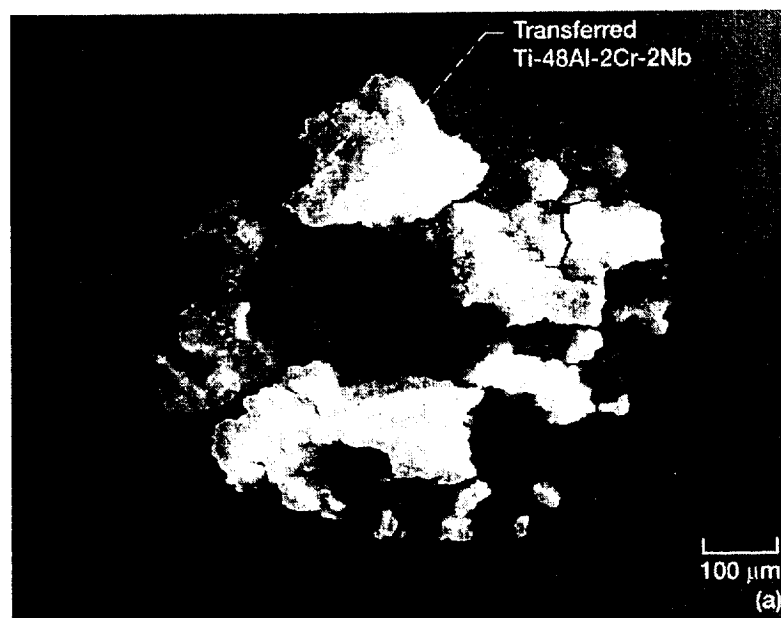


Figure 2.—Wear scar on IN718 pin fretted against Ti-48Al-2Cr-2Nb flat in air at 550 °C.
(a) SEM backscattered electron image. (b) X-ray energy spectrum with EDS.

4.0 RESULTS AND DISCUSSION

4.1 Observations

Surface and subsurface damage always occurred on the interacting surfaces of titanium-base alloys fretted in air. The surface damage consisted of material transfer, pits, oxide and debris, scratches, fretting craters and/or wear scars, plastic deformation, and cracks.

4.1.1 Adhesion and material transfer

Ti-48Al-2Cr-2Nb.— Figure 2 presents a backscattered electron image and an energy-dispersive x-ray (EDX) spectrum taken from the fretted surface of the IN718 pin after contact with the Ti-48Al-2Cr-2Nb flat. Clearly,

Ti-48Al-2Cr-2Nb transferred to the IN718. The Ti-48Al-2Cr-2Nb failed either in tension or in shear because some of the interfacial adhesive bonds (solid-state or cold welding) were stronger than the cohesive bonds in the cohesively weaker Ti-48Al-2Cr-2Nb. The failed Ti-48Al-2Cr-2Nb subsequently transferred to the IN718 surface in amounts ranging from 10 to 60 percent of the IN718 contact area at all fretting conditions in this study. The thickness of the transferred Ti-48Al-2Cr-2Nb ranged up to approximately 20 μm .

Ti-6Al-4V.—As with the materials pair of Ti-48Al-2Cr-2Nb and IN718, material transfer was observed on the IN718 flat surface after fretting against the Ti-6Al-4V pin at 23 and 550 $^{\circ}\text{C}$ in air. However, the degree of material transfer was remarkably different and greater, ranging from 30 to 100 percent of the IN718 contact area. The thickness ranged up to 50 μm .

4.1.2 Fretting wear

Figure 3 shows typical wear scars produced on the Ti-48Al-2Cr-2Nb pin after contact with the IN718 flat. Because of the specimen geometry a large amount of wear debris was deposited just outside the circular contact area. Pieces of the metals (both Ti-48Al-2Cr-2Nb and IN718) and their oxides were torn out during fretting. It appears that the cohesive bonds in some of the contact area of both metals fractured. Scanning electron microscopy (SEM) and EDX studies of wear debris produced under fretting verified the presence of metallic Ti-48Al-2Cr-2Nb particles and IN718 particles. In the central region of wear scars produced on Ti-48Al-2Cr-2Nb there was generally a large, shallow pit where the Ti-48Al-2Cr-2Nb had torn out or sheared off and subsequently transferred to the IN718. The central regions of wear scars produced on Ti-48Al-2Cr-2Nb and on IN718 were morphologically similar, as shown in figure 3, generally having wear debris, scratches, plastically deformed asperities, and cracks.

Figure 4 shows examples of surface damage: metallic wear debris of Ti-48Al-2Cr-2Nb and IN718, oxides and their debris, scratches (grooves), small craters, plastically deformed asperities, and cracks. The scratches (fig. 4(a)) can be caused by hard protuberances (asperities) on the IN718 surface (two-body conditions) or by hard wear particles between the surfaces (three-body conditions). Abrasion is a severe form of wear. The hard asperities and trapped hard particles plow or cut the Ti-48Al-2Cr-2Nb surface. The trapped hard particles have a scratching effect on both surfaces; and because they carry part of the load, they cause concentrated pressure peaks on both surfaces as they try to penetrate them. The pressure peaks may well be the origin of crack nucleation in the oxide layers and the bulk alloys. Two types of crack were observed on the wear surface of Ti-48Al-2Cr-2Nb: cracks in oxide layers, and cracks in bulk Ti-48Al-2Cr-2Nb.

Oxide layers readily form on the Ti-48Al-2Cr-2Nb surface at 550 $^{\circ}\text{C}$ and are often a favorable solution to wear problems. However, if the bulk Ti-48Al-2Cr-2Nb is not hard enough to carry the load, it will deform plastically or elastically under fretting contact. With Ti-48Al-2Cr-2Nb, cracks occurred in the oxide layers both within and around the contact areas (fig. 4(b)).

Fractures in the protective oxide layers produced cracks in the bulk Ti-48Al-2Cr-2Nb (fig. 4(c)) and produced wear debris; chemically active, fresh surfaces; plastic deformation; and craters or fracture pits (fig. 4(d)). The wear

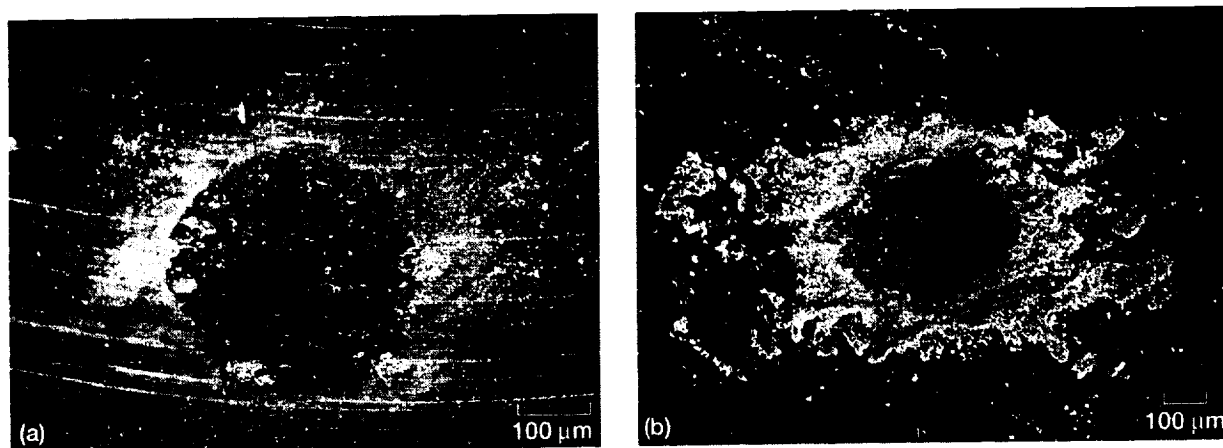


Figure 3.—Wear scars (a) on Ti-48Al-2Cr-2Nb pin and (b) on IN718 flat in air at 550 $^{\circ}\text{C}$.

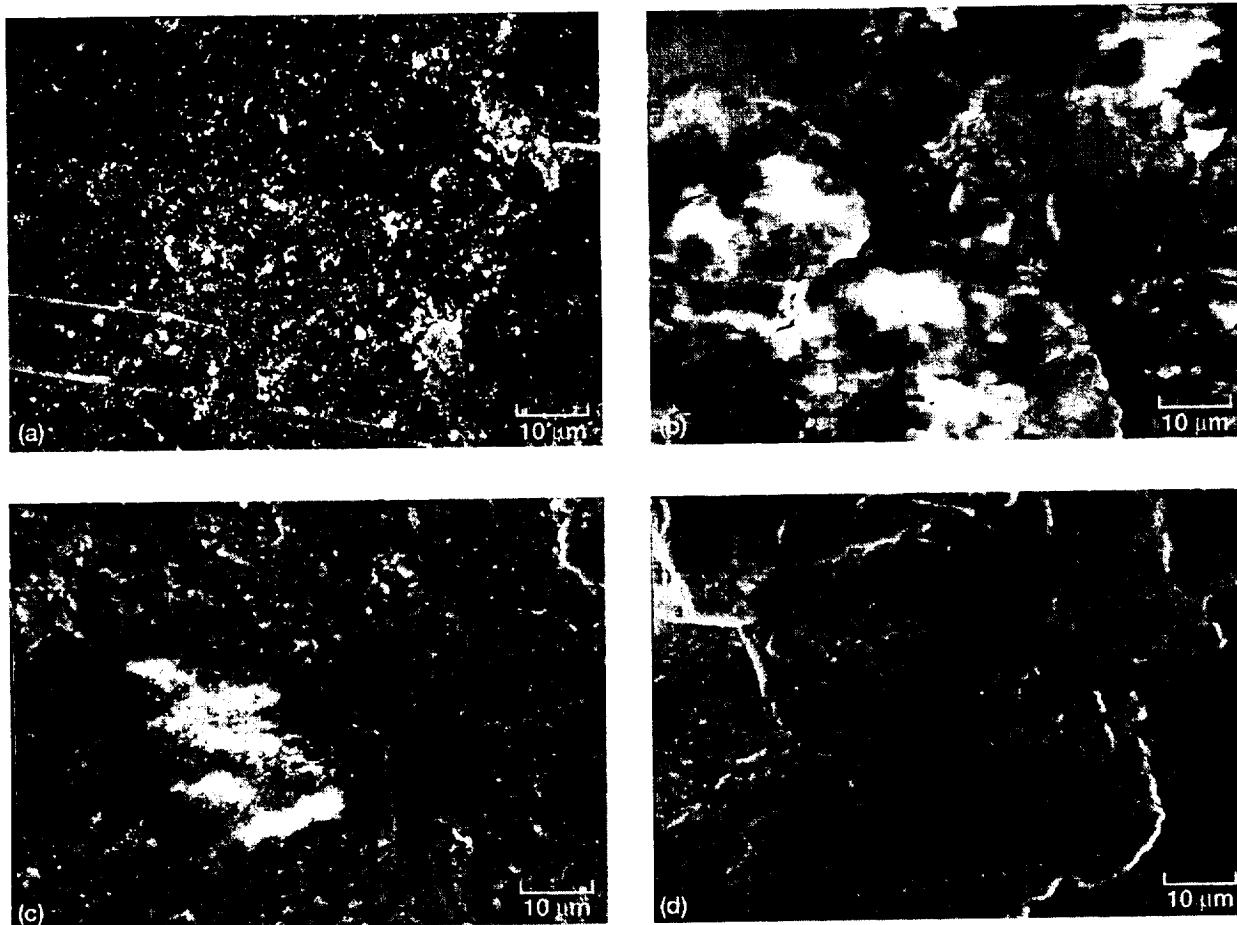


Figure 4.—Surface and subsurface damage in Ti-48Al-2Cr-2Nb flat in contact with IN718 pin in air at 550 °C.
(a) Scratches. (b) Cracks in oxide layers. (c) Cracks in metal. (d) Fracture pits and plastic deformation.

debris caused third-body abrasive wear, as shown in figure 4(a). Local, direct contacts between the fresh surfaces of Ti-48Al-2Cr-2Nb and IN718 resulted in increased adhesion and local stresses, which may cause plastic deformation, flake-like wear debris, and craters (e.g., the fracture pits shown in fig. 4(d)) in the Ti-48Al-2Cr-2Nb.

Cross sections of the wear scar on Ti-48Al-2Cr-2Nb revealed subsurface cracking and craters. For example, figure 5 shows propagation of subsurface cracking, nucleation of small cracks, formation of a large crater, and generation of debris.

4.2 Parameters Influencing Wear Loss of Ti-48Al-2Cr-2Nb

Figure 6(a) shows the measured wear volume loss as a function of fretting frequency for Ti-48Al-2Cr-2Nb in contact with IN718 at temperatures of 23 and 550 °C and a load of 30 N, with a slip amplitude of 50 μm, for 1 million cycles. Although there were some exceptions, the wear volume loss generally decreased with increasing fretting frequency. A reasonable amount of material transfer from the Ti-48Al-2Cr-2Nb specimen to the IN718 specimen was observed at any frequency. At the lowest frequency of 50 Hz, material transfer from the IN718 to the Ti-48Al-2Cr-2Nb and remarkable plastic deformation (grooving) and surface roughening in the Ti-48Al-2Cr-2Nb wear scar were observed. At high frequencies almost no material transferred from the IN718 to the Ti-48Al-2Cr-2Nb, and wear scars were noticeably smooth with bulk cracks.

The environment, particularly temperature, influences the adhesion, deformation, and fracture behaviors of contacting materials in relative motion. The temperature interacts with the fretting process in two ways: The rate of oxidation or corrosion increases with temperature; and the mechanical properties, such as hardness, of the materials are usually affected by temperature (ref. 9). Figure 6(b) presents the measured wear volume loss as a function of

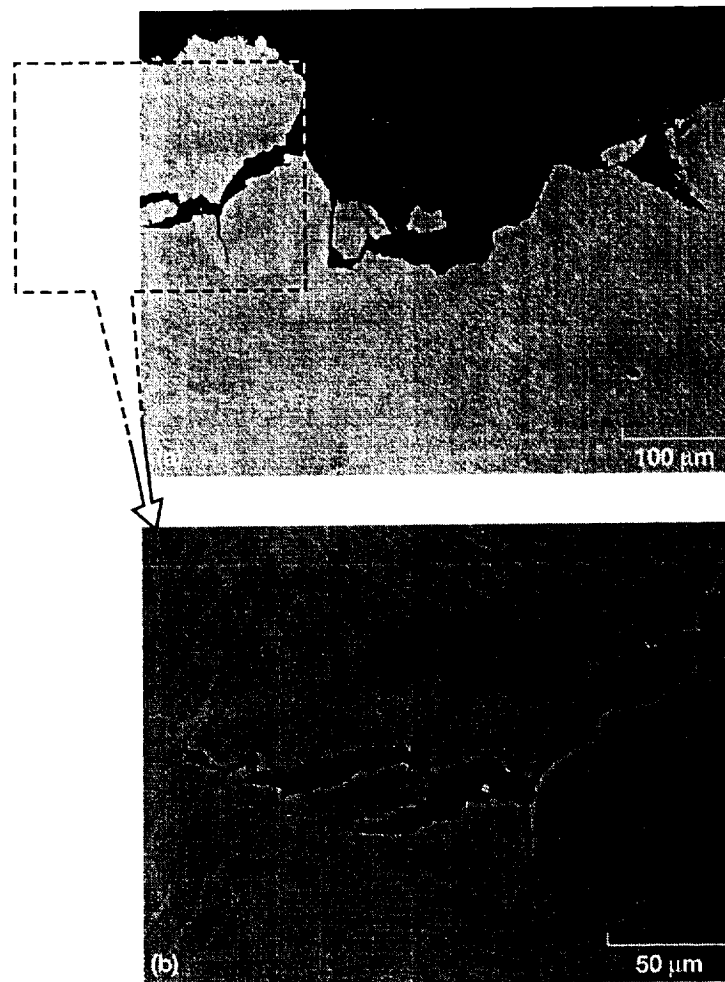


Figure 5.—Cross-section view of wear scar on Ti-48Al-2Cr-2Nb flat in contact with IN718 pin in air at 550 °C. (a) An overview. (b) Crack growth.

temperature for Ti-48Al-2Cr-2Nb in contact with IN718 at several fretting frequencies (50, 80, 120, and 160 Hz), a load of 30 N, and a slip amplitude of 50 μm for 1 million cycles. The wear volume loss dropped to a low value at 200 °C because a protective oxide film prevented direct metal-to-metal contact and ensured, in effect, that a mild oxidative wear regime prevailed. However, fretting wear increased as the temperature was increased from 200 to 550 °C. The highest temperatures of 450 and 550 °C resulted in oxide film disruption with crack generation, loose wear debris, and pitting of the Ti-48Al-2Cr-2Nb wear surface.

Figure 7 shows the measured volume loss as a function of slip amplitude for Ti-48Al-2Cr-2Nb in contact with IN718 at temperatures of 23 and 550 °C, a load of 30 N, and a fretting frequency of 50 Hz, with a slip amplitude of 50 μm , for 1 million cycles. The fretting wear volume loss generally increased as the slip amplitude increased. Increases in amplitude tend to produce more metallic wear debris, causing severe abrasive wear in the contacting metals. Figure 8 presents a three-dimensional view of the Ti-48Al-2Cr-2Nb wear scar at a slip amplitude of 200 μm and a temperature of 23 °C. In the wear scar are large, deep grooves where the wear debris particles have scratched the Ti-48Al-2Cr-2Nb surface in the slip direction.

Figure 9 shows the measured wear volume loss as a function of load for Ti-48Al-2Cr-2Nb in contact with IN718 at a temperature of 550 °C, a fretting frequency of 80 Hz, with a slip amplitude of 50 μm , for 1 million cycles. The fretting wear volume loss generally increased as the load increased, generating more metallic wear debris in the contact area, the primary cause of abrasive wear in both Ti-48Al-2Cr-2Nb and IN718.

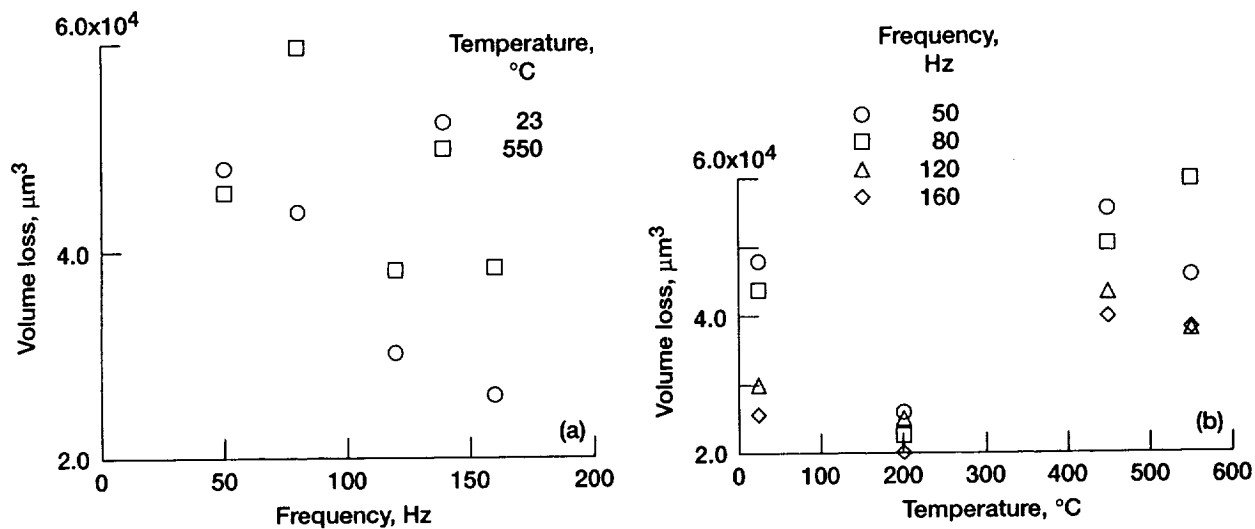


Figure 6.—Wear volume loss of Ti-48Al-2Cr-2Nb flat in contact with IN718 pin in air as function of (a) fretting frequency and (b) temperature.

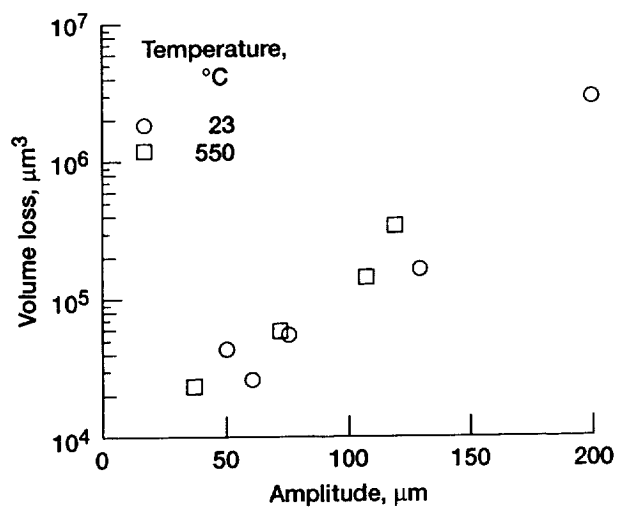


Figure 7.—Wear volume loss of Ti-48Al-2Cr-2Nb flat in contact with IN718 pin in air as function of fretting amplitude.

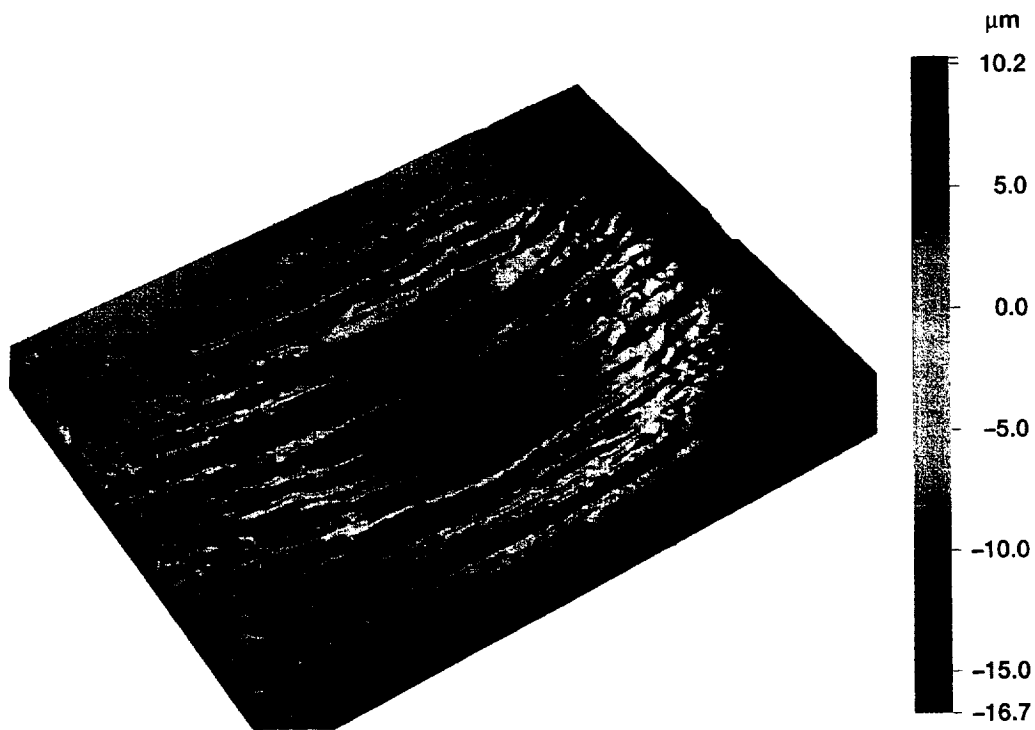


Figure 8.—Wear scar on Ti-48Al-2Cr-2Nb flat in contact with IN718 pin in air at 23 °C, showing scratches.

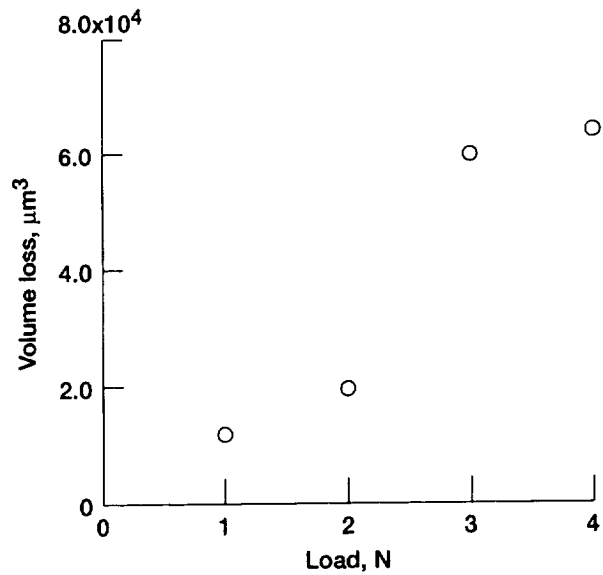


Figure 9.—Wear volume loss of Ti-48Al-2Cr-2Nb flat in contact with IN718 pin in air at 550 °C as function of load.

5. CONCLUDING REMARKS

In this investigation to examine the fretting behavior of γ -TiAl (Ti-48Al-2Cr-2Nb) in contact with a nickel-base superalloy (Inconel 718) in air at temperatures of 23 to 550 °C the following results were observed:

1. The Ti-48Al-2Cr-2Nb transferred to the IN718 at any fretting condition, ranging from 10 to 50 percent of the IN718 contacting surface area. The maximum thickness of the transferred Ti-48Al-2Cr-2Nb was approximately 20 μ m.
2. The wear scars produced on the Ti-48Al-2Cr-2Nb contained metallic and oxide wear debris, scratches, plastically deformed asperities, cracks, and fracture pits.
3. Although oxide layers readily formed on the Ti-48Al-2Cr-2Nb surface at 550 °C, cracks easily occurred in the oxide layers both within and around the contact areas.
4. The wear volume loss of Ti-48Al-2Cr-2Nb generally decreased with increasing frequency, increased with increasing temperature, and increased with increasing slip amplitude.
5. The wear volume loss dropped to a low value at 200 °C because a mild oxidative wear regime prevailed.

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